Precision Data and Implications on the Parameters of TC theory*

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Abstract

Assuming that the actual values of m_t and the data set (Γ_b, Γ_h, Γ_Z, R_b, R_c, R_l) are within their $1-\sigma$ errors as reported by CDF, D0 and by LEP Collaborations, the parameter Δ_b^{new} which measures the nonoblique corrections on the $Zb\bar{b}$ vertex from new physics can be determined experimentally. According to the precision data one can obtain updated constraints on the parameters ξ and the masses of the charged PGBs.

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1. Introduction

As is well known, the Standard Model [1] predictions for the electroweak observables are in perfect agreement with the current data [2, 3]. But frankly speaking, the SM is also a complicated theory with many free parameters and other open questions. Very recently the discovery of the top quark has been announced by CDF with $M_t = 176 \pm 8 \pm 10\ GeV$ [4], which we interprete as $M_t = 176 \pm 13\ GeV$, and by the D0 Collaboration with $M_t = 199^{+19}_{-21} \pm 22\ GeV$[5]). This direct measurement of top quark mass is in very good agreement with the prediction based on the SM electroweak fits of the LEP and other data, $M_t = 178 \pm 8^{+17}_{-18}\ GeV$[3], where the central value and the first error refer to $M_H = 300\ GeV$. This direct measurement of M_t, while still not very precise, should help in reducing the present uncertainties on almost all electroweak observables. And consequently, the knowledge of M_t will be very important for one to look for the hints of new physics.

Technicolor(TC) [6] is one of the important candidates for the mechanism of electroweak symmetry breaking. The comparison of theoretical predictions based on the TC theories and the precision electroweak measurements is very specialized and rapidly changing, as new data becomes available as well as new theoretical variables with which theory can be compared with experiment. This subject is of immense importance to TC theory, because it has been widely reported that the data disfavor TC theories, a claim that has been disputed by several authors (for a recent review see ref.[7]).

Very recently, Burgess et al., [8] extended the (S,T,U) parametrization[9] by introducing three additional parameters (V,W,X) to describe the lowest non-trivial momentum dependence in oblique diagrams. The inclusion of (V, W, X) in the fit weakens the bounds on S, T strongly: $S < 2.5$, $T < 1.3$ [7, 8].

In this paper we define a parameter Δ_b^{new} which only measures the non-oblique corrections on $Zb\bar{b}$ vertex from new physics, especially that from the ETC dynamics and the charged PGBs appeared in QCD-like TC theories. By the comparison of the theoretical prediction for Δ_b^{new} in TC theory with the experimentally determined $\Delta_{b,exp}^{new}$ one can obtain some constraints on the Clebsch-Gordon coefficient ξ and put new lower limits on the masses of charged PGBs.

This paper is organized as follows: In Sec.2 we at first present the standard model predictions for R_b and other observables and then define the new parameter Δ_b^{new}. In Sec.3 are collected the relevant calculations and the constraints for the parameter ξ and the masses m_{p1} and m_{p2} for QCD-like TC theories. We also list and comment on several new TC models proposed very recently in the sense of avoiding the existed constraints imposed by the precision data. The conclusions and the related discussions are in Sec.4.

2. $Zb\overline{b}$ veretx, the SM predictions and the data

For LEP processes there are two types of radiative corrections: the corrections to the gauge boson self-energies and the corrections to the $Zb\overline{b}$ vertex. In the evaluation of self-energy corrections the error due to our ignorance of the Higgs mass is substantial after the direct measurement of m_t at Fermilab[4, 5]. On the other hand, in the corrections to the $Zb\overline{b}$ vertex, where the leading contribution due to the large top quark mass is produced by the exchange of the W bosons, there is no dependence on the unknown Higgs mass. Moreover, the possible new physics contributions to the $Zb\overline{b}$ vertex are much more restricted. Any non-standard behavior most possibly means the existence of new physics!

The Z-pole observables considered in this paper include Γ_b, Γ_h, Γ_Z, R_b, R_c and R_l (in which $\Gamma_l = (\Gamma_e + \Gamma_\mu + \Gamma_\tau)/3$), they are well determined theoretically and experimentally. Because the asymmetry A_{FB}^b is almost unaffected by the $Zb\overline{b}$ vertex correction [10] we will not include this quantity in our analysis.

Calculations of the one-loop corrections to the $Zb\overline{b}$ vertex has been performed by several groups [11]. The partial decay width $\Gamma(Z \to f\overline{f})$ has been calculated in the $\overline{MS}$ renormalization scheme [12] and has been expressed in a compact form [13],

$$\begin{aligned}\Gamma(Z \to f\overline{f}) &= \frac{N_c^f}{48}\frac{\hat{\alpha}}{\hat{s}_w^2\hat{c}_w^2} m_Z[\hat{a}_f^2 + \hat{v}_f^2](1+\delta_f^{(0)})(1+\delta_{QED}^f) \\ &\quad \cdot(1+\delta_{QCD})(1+\delta_\mu^f)(1+\delta_{tQCD}^f)(1+\delta_b),\end{aligned} \tag{1}$$

where $N_c^f = 3(1)$ for quarks (leptons) is the color factor. The partial decay widths in eq.(1) has included the genuine electroweak corrections, the QED and QCD corrections, as well as the corrections to $Zb\overline{b}$ vertex due to the large top quark mass. The definitions

and the explicit expressions for all functions and factors appeared in eq.(1) can be found in refs.[12, 13]. In ref.[14], J.Fleischer et al. calculated the two-loop $0(\alpha\alpha_s)$ QCD corrections to the partial decay width Γ_b, and they found a screening of the leading one-loop top mass effects by $m_t \to m_t\,[1 - \frac{1}{3}(\pi^2 - 3)\alpha_s/\pi]$. In this paper we will include this two-loop QCD corrections. For more details about the calculations of Γ_b and other relevant quantities in the SM one can see the refs.[11, 12] and a more recent paper[15].

In our analysis, the measured values [2, 16, 17, 4] $m_Z = 91.1888 \pm 0.0044 \;\; GeV$, $G_\mu = 1.16639 \times 10^{-5} (GeV)^{-2}$, $\alpha^{-1} = 137.0359895$, $\alpha_s(m_Z) = 0.125 \pm 0.005$, $m_e = 0.511 \; MeV$, $m_\mu = 105.6584 \; MeV$ and $m_\tau = 1776.9 \; MeV$, together with $m_t = 176 \pm 13 \, GeV$ and the assumed value $M_H = 300^{+700}_{-240} \; GeV$ are used as the input parameters. In the numerical calculations we conservatively take the "on-shell" mass of the b-quark the value $m_b = 4.6 \pm 0.3 \; GeV$ (in ref.[13], the authors used $m_b = 4.6 \pm 0.1 \; GeV$), and use the known relation[18]between the "on-shell" and the $\overline{MS}$ schemes to compute the running mass $\overline{m}_b(m_Z)$ at the Z scale: $\overline{m}_b(m_Z) = 3 \pm 0.2 \; GeV$ for $m_Z = 91.1888 \; GeV$. We also use the same treatment for the c-quark, $\overline{m}_c(m_Z) = 1 \, GeV$ if we take $m_c = 1.6 \, GeV$ as its "on-shell" mass. For other three light quarks we simply assume that $\overline{m}_i(m_Z) = 0.1 \, GeV$ $(i = u, d, s)$. All these input parameters will be referred to as the *Standard Input Parameters* (SIP).

Among the electroweak observables the ratio $R_b = \Gamma_b / \Gamma_h$ is the special one. For this ratio most of the vacuum polarization corrections depending on the m_t and m_h cancel out, while the experimental uncertainties in the detector response to hadronic events also basically cancel. Furthermore, this ratio is also insensitive to extensions of the SM which would only contribute to vacuum polarizations.

In Table 1 we list the SM predictions for the Z boson decay widths (in MeV) and the ratios R_b, $R_c = \Gamma(Z \to c\overline{c})/\Gamma_h$ and $R_l = \Gamma_h / \Gamma(Z \to l\overline{l})$, the corresponding measured values at LEP are also listed. It is easy to see that the R_b predicted by the SM is smaller than that measured. The deviation reaches 2.2-σ (or 2.5-σ at one-loop order) for $m_t = 176 \, GeV$.

The precision data can be used to set limits on TC theory as well as other kinds of possible new physics. Besides the m_t dependence the $Zb\overline{b}$ vertex is also sensitive to a

number of types of new physics. One can parametrize such effects by

$$\Gamma_b = \Gamma_b^{SM}(1 + \Delta_b^{new}) \tag{2}$$

where the term Δ_b^{new} represents the pure non-oblique corrections to the $Zb\bar{b}$ veretx from new physics. The partial decay width Γ_b^{SM} can be determined theoretically by eq.(1), and consequently other five observables studied in this paper can be written as the form of

$$\begin{aligned}
\Gamma_h &= \Gamma_h^{SM} + \Gamma_b^{SM} \cdot \Delta_b^{new}, \qquad \Gamma_Z = \Gamma_Z^{SM} + \Gamma_b^{SM} \cdot \Delta_b^{new}, \\
R_b &= R_b^{SM} + R_b^{SM}(1 - R_b^{SM}) \cdot \Delta_b^{new}, \qquad R_c = R_c^{SM} - R_b^{SM} R_c^{SM} \cdot \Delta_b^{new}, \\
R_l &= R_l^{SM} + \frac{\Gamma_b^{SM}}{\Gamma_l^{SM}} \cdot \Delta_b^{new}.
\end{aligned} \tag{3}$$

Obviously, the oblique corrections and the heavy top quark vertex effect have been absorbed into the evaluations for the observables X_i^{SM} in the SM. This definition of Δ_b^{new} in eq.(2) is different from that of ϵ_b [10](as well as the parameter Δ_b in refs.[19, 20]). In the SM the parameters ϵ_b[10] and Δ_b[20] are closely related to the quantity $-Re\{\delta_{b-vertex}\}$ defined in ref.[13] and are dominated by quadratic terms in m_t of order $G_F m_t^2$. While the parameter Δ_b^{new} only measures the new physics effects on the $Zb\bar{b}$ vertex, and $\Delta_b^{new} \equiv 0$ in the SM. We think that this definition of Δ_b^{new} is more convenient than other similar definitions to measure the new physics effects on the $Zb\bar{b}$ vertex, since new physics can be disentangled if not masked by large m_t effects.

In order to extract the vertex factor Δ_b^{new} from the data set $(\Gamma_b, \Gamma_h, \Gamma_Z, R_b, R_c, R_l)$ as listed in Table 1 more quantitatively, we construct the likelihood function of Δ_b^{new} as the form of

$$\mathcal{L}(x_{exp}, \Delta_b^{new}) = N\, Exp[-\sum_x \frac{1}{2}(\frac{x_{exp} - x(\Delta_b^{new})}{\sigma_x})^2] \tag{4}$$

where the σ_x is the experimental error of the observable x_{exp}, and N is the normalization factor. With the SIP, the point which maximizes $\mathcal{L}(x_{exp}, \Delta_b^{new})$ is found to be $\Delta_b^{new} = 0.001$ for $m_t = 176\ GeV$. And we also have

$$\Delta_b^{new} = 0.001 \pm 0.005 \tag{5}$$

at $1-\sigma$ level for $m_t = 176\ GeV$ and $M_H = 300\ GeV$, while the remainder uncertainties of Δ_b^{new} are ± 0.002 and ${}^{+0.004}_{-0.002}$ corresponding to $\delta m_t = 13\,GeV$ and $M_H = 300^{+700}_{-240}$ respectively. It is easy to see that Δ_b^{new} is now consistent with zero at $1-\sigma$ level. By its own

definition the parameter Δ_b^{new} has no dependence on M_H, the present weak dependence is coming from the standard model calculations for the six observables. In the following analysis we always use ($m_t = 176\,GeV$, $M_H = 300\,GeV$) as reference point and don't discuss the variation of M_H.

If we interpret the quantity

$$P(\Delta_b^{new} > A) = \int_A^{+\infty} d\Delta_b^{new} \mathcal{L}(x_{exp}, \Delta_b^{new}) \tag{6}$$

and

$$P(\Delta_b^{new} < B) = \int_{-\infty}^{B} d\Delta_b^{new} \mathcal{L}(x_{exp}, \Delta_b^{new}) \tag{7}$$

as the probability that $\Delta_b^{new} > A$ ($\Delta_b^{new} < B$), then one can obtain the 95% one-sided upper (lower) confidence limits on Δ_b^{new}:

$$\Delta_{b,exp}^{New} > -0.010, \quad and \quad \Delta_{b,exp}^{New} < 0.012 \tag{8}$$

for $m_t = 176 \pm 13\, GeV$.

For any kinds of new physics which may contribute to the $Zb\overline{b}$ vertex, they should satisfy this constraint from $Zb\overline{b}$ vertex as well as those from the (S, T, U, V, W, X) oblique parameters simultaneously.

3. Updated constraints on ξ and masses of charged PGBs

In the TC models [6, 7, 21], the larger top quark mass is presumably the result of ETC [22] dynamics at relatively low energy scales. There are two sources of corrections to this $Zb\overline{b}$ vertex in TC models, namely from ETC gauge boson exchange [23, 24] and from charged PGB exchange [25, 26]

For the One-Doublet Technicolor Model(ODTM)[27], no Pseudo-Goldstone bosons can be survived when the chiral symmetry was broken by the condensate $< T\overline{T} > \neq 0$, but the ETC gauge boson exchange can produce typically large and negative contributions to the $Zb\overline{b}$ vertex, as described in ref.[23],

$$\Delta_1^{ETC} \approx -6.5\% \times \xi^2 \cdot [\frac{m_t}{176GeV}] \tag{9}$$

where the constant ξ is an ETC-gauge-group-dependent Clebsch-Gordon coefficient and expected to be of order 1 [23]. Theoretically, the exact value of ξ will be determined by the choice of ETC gauge group and by the assignments of the technifermions. As shown in eq.(9), the non-oblique correction on the $Zb\overline{b}$ vertex from the ETC dynamics is quadratic in ξ. The variation of ξ will strongly affect the size of Δ_1^{ETC}. Naturally the experimental limits on the vertex factor Δ_b^{new} cab be interpreted as the bounds on ξ. For $m_t = 189\, GeV$ one can have,

$$\xi < 0.4, \quad at \ \ 95\% \, C.L. \tag{10}$$

For lighter top quark this bound will be loosened slightly.

In the most frequently studied Farhi-Susskind One Generation Technicolor Model (OGTM) [27], the global flavor symmetry $SU(8)_L \times SU(8)_R$ will break down to the $SU(8)_V$ by technifermion condensate $< \overline{T}T > \neq 0$. And consequently 63 massless (Pseudo)-Goldstone bosons will be produced from this breaking. Besides the nonoblique corrections Δ_2^{ETC} from the ETC gauge boson exchange, the charged PGBs in the OGTM also contribute a negative correction to the $Zb\overline{b}$ vertex as estimated in ref.[25, 26]. In short,

$$\Delta_b^{new}(OGTM) = \Delta_2^{ETC} + \Delta_b^{P^\pm} + \Delta_b^{P_8^\pm}. \tag{11}$$

where the terms $\Delta_b^{P^\pm}$ and $\Delta_b^{P_8^\pm}$ represent the contributions from the color singlet charged PGBs $P^\pm$ and the color octets $P_8^\pm$. Specifically, all three terms in the right-hand side of this equation are negative.

For simplicity, we assume that the ETC part of the OGTM studied here are the same or very similar with the ODTM studied in ref.[23] except for the difference in the value of F_π (in the OGTM, $F_\pi = 123\, GeV$), and then we can write

$$\Delta_2^{ETC} \approx -12.9\% \times \xi^2 \cdot [\frac{m_t}{176GeV}] \tag{12}$$

Typically, $\Delta_2^{ETC} \approx -6.5\%$ for $m_t = 176\, GeV$ and $\xi = 1/\sqrt{2}$, which is consistent with the result as shown in the Fig.3 of ref.[24] for the $SU(4)_{ETC} \rightarrow SU(3)_{TC}$ model with a full family of technifermions.

In ref.[25, 26], we have calculated the non-oblique corrections on the $Zb\overline{b}$ vertex from the color singlet PGBs $P^\pm$ and the color octet PGBs $P_8^\pm$ respectively. The size of the

vertex factor $\Delta_b^{P^\pm}$ ($\Delta_b^{P_8^\pm}$) depends on m_t and m_{p1} (m_{p2}). Using the SIP, one can estimate the ranges of the term $\Delta_b^{P^\pm}$ and $\Delta_b^{P_8^\pm}$:

$$\Delta_b^{P^\pm} = (-0.013 \sim -0.002), \; for \;\; m_{p1} = 50 - 400\, GeV, \tag{13}$$

$$\Delta_b^{P_8^\pm} = (-0.050 \sim -0.003), \; for \;\; m_{p2} = 200 - 650\, GeV, \tag{14}$$

where m_{p1} is the mass of $P^\pm$, and m_{p2} is the mass of $P_8^\pm$. The contributions from the charged PGBs are always negative and will push the OGTM prediction for Δ_b^{new} away from the measured $\Delta_{b,exp}^{New}$ to a high degree. These negative corrections are clearly disfavored by the current data. But fortunately, the charged PGBs show a clear decoupling behavior as listed in eqs.(13, 14).

In the OGTM, the size of vertex factor Δ_b generally depend on three " free" parameters, the Clebsch-Gordon coefficient ξ, the masses m_{p1} and m_{p2} if we use $m_t = 176 \pm 13$ GeV as input. In order to study the nonoblique corrections on the $Zb\overline{b}$ vertex more quantitatively, we consider the following two ultimate cases: (a). Under the limit $\xi \rightarrow 0$, to extract the possible bounds on the masses of m_{p1} and m_{p2}; (b). Under the limits $\Delta_b^{P^\pm} \rightarrow 0$ and $\Delta_b^{P_8^\pm} \rightarrow 0$(e.g. the charged PGBs are heavy enough and decoupled from the low energy physics), to extract the bounds on the parameter ξ.

At first if we set $\xi \rightarrow 0$ the current data will permit us to exclude large part of the ranges of m_{p1} and m_{p2} in the $m_{p1} - m_{p2}$ plan, the updated bounds on the masses of charged PGBs are the following:

$$m_{p1} > 200\, GeV \;\; at \;\; 95\%\, C.L., \;\; for \;\; \text{"}free\text{"} \;\; m_{p2} \tag{15}$$

and

$$m_{p2} > 600\, GeV \;\; at \;\; 95\%\, C.L., \;\; for \;\; m_{p1} \leq \; 400\, GeV. \tag{16}$$

while the uncertainties of m_t, $\delta m_t = 13\, GeV$, almost don't affect the constraints. These limits are much stronger than that has been given before in ref.[26]. Of cause, the inclusion of the negative corrections from ETC dynamics in the OGTM will strengthen the bounds on m_{p1} and m_{p2}.

Secondly, if we set the limits $\Delta_b^{P^\pm} \rightarrow 0$ and $\Delta_b^{P_8^\pm} \rightarrow 0$, the current data means a stringent bound on the size of ξ in the OGTM: $\xi < 0.28$ at 95% $C.L.$ for $m_t = 189\, GeV$.

If the charged PGBs are heavy and decoupled and, at the same time, the coefficient ξ in QCD-like TC models can be reduced to 0.28 instead of the popular size $1/\sqrt{2}$ as used in ref.[24], the magnitude of both the $\Delta_b^{new}(ODTM)$ and $\Delta_b^{new}(OGTM)$ will be consistent with the present constraints on Δ_b^{new}.

4. Conclusions

As mentioned at the beginning, TC theory can provide a natural, dynamical explanation for electroweak symmetry breaking. But, as is well known, this theory (including the ETC) also encountered many problems as discussed in detail in refs.[7]. At present, the situation becomes better than 3 years ago[28]. The experimentally determined parameters S_{exp} and $\Delta_{b,exp}^{new}$ are all close to zero with small errors, and therefore the former strong constraints are now weakened.

In ref.[24], the authors have shown that a slowly running technicolor coupling will affect the size of non-oblique corrections to the $Zb\bar{b}$ vertex from ETC dynamics. Numerically, the "Walking TC" [29] reduces the magnitude of the corrections at about 20% level. Although this decrease is helpful to reduce the discrepancy between the TC models and the current precision data, however, this improvement is not large enough to resolve this problem. More recently, N.Evans[30] points out that the constraints from $Zb\bar{b}$ veretx may be avoided if the ETC scale M_{ETC} can be boosted by strong ETC effects.

For standard ETC dynamics[22, 7] the ETC gauge bosons are the $SU(2)_w$ singlets, and the exchanges of such kinds of ETC gauge bosons will produce large negative corrections to the $Zb\bar{b}$ vertex as described in refs.[23, 24]. In "Non-commuting" theories (i.e., in which the ETC gauge boson which generates the top quark mass does carry weak SU(2) charge), as noted in refs.[23, 31], the contributions on the $Zb\bar{b}$ vertex come from the physics of top-quark mass generation and from weak gauge boson mixing (the signs of the two effects are opposite)[31], and therefore both the size and the sign of the corrections are model dependent and the overall effect may be small and may even increase the $Zb\bar{b}$ branching ratio. It is important to explore this class of models further, since the experiments favor a larger R_b[15].

Besides the new TC models just mentioned above several TC models with novel

ideas have also been constructed since 1993, such as the "Low-scale technicolor"[32], the "Technicolor model with a scaler" [33], the " Topcolor assisted technicolor" [34], "Chiral technicolor"[35] and other models. The main motivation for constructing these new models is evident: Generating the larger top quark mass and at the same time being consistent with the precision data.

In summary we defined a parameter Δ_b^{new} which measures the non-oblique corrections on the $Zb\bar{b}$ vertex from the new physics, such as the ETC dynamics and the charged PGBs appeared in QCD-like TC theories. By its own definition the parameter Δ_b^{new} is different from the ϵ_b and the Δ_b as defined in refs. [10, 19], and this parameter can be determined experimentally from the data set (Γ_b, Γ_h, Γ_Z, R_b, R_c, R_l). By the comparison of the theoretical prediction for Δ_b^{new} in QCD-like TC theories with the experimentally determined $\Delta_{b,exp}^{new}$ one can obtain some constraints on the Clebsch-Gordon coefficient ξ and put more stringent lower limits on the masses of charged PGBs. From the numerical calculations and the phenomenological analysis we found that:

(a). The charged Pseudo-Goldstone bosons must be heavier than that estimated before in Ref.[25]. At present for $m_t = 176 \pm 13\ GeV$, we have $m_{p1} > 200\ GeV$ at $95\% C.L$ for "free" m_{p2}, and $m_{p2} > 600\ GeV$ at $95\% C.L$ for $m_{p1} \leq 400\ GeV$;

(b). If the charged PGBs are indeed very heavy and decoupled and, at the same time, the coefficient ξ in the new QCD-like TC models can be smaller than 0.28, such kinds of QCD-like TC models still be allowed.

(c). There is definite discrepancy about the value of R_b between the SM and the experiment. But at present it is hard to explain this deviation as a signal of new physics. From the data set of $(\Gamma_b, \Gamma_h, \Gamma_Z, R_b, R_c, R_l)$, one can determine the size of the nonoblique corrections on the $Zb\bar{b}$ vertex from the new physics experimentally: $\Delta_{b,exp}^{new} = 0.001 \pm 0.005 \pm 0.002(m_t)$, which is close to zero with small errors.

Table 1. The SM predictions for the observables ($\Gamma_b,\ \Gamma_h,\ \Gamma_Z,\ R_b,\ R_c,\ R_l$), compared with the measured Z parameters at LEP.

	SM Predictions	LEP Values
Γ_b	$377.7 \pm 0.2(m_t)^{+0.2}_{-0.9}(m_h) \pm 0.5(\alpha_s) \pm 0.4(\hat{\alpha}) \pm 0.3(\overline{m}_b)$	382.7 ± 3.1, [10]
Γ_h	$1749.3\ \pm 3.2(m_t)\ ^{+1.4}_{-4.5}(m_h)\ \pm 2.9(\alpha_s)\ \pm 1.7(\hat{\alpha})\ \pm 0.3(\overline{m}_b)$	1745.9 ± 4.0, [2]
Γ_Z	$2503.9\ \pm 4.3(m_t)\ ^{+1.2}_{-5.9}(m_h)\ \pm 2.9(\alpha_s)\ \pm 2.4(\hat{\alpha})\ \pm 0.3(\overline{m}_b)$	2497.4 ± 3.8, [2]
R_b	$0.2159 \pm 0.0005(m_t) \pm 0.00003(m_h) \pm 0.00004(\alpha_s)\ \pm 0.0001(\overline{m}_b)$,	0.2202 ± 0.0020, [2]
R_c	$0.1721\ \pm 0.0002(m_t)\ \pm 0.00004(m_h)\ \pm 0.0001(\alpha_s) \pm 0.00003(\overline{m}_b)$,	0.1583 ± 0.0098,[2]
R_l	$20.820 \pm 0.002(m_t) \pm 0.015(m_h) \pm 0.034(\alpha_s) \pm 0.003(\overline{m}_b)$	20.795 ± 0.040, [2]

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